北海道大学工学部研究報告
第79号（昭和51年）

Bulletin of the Faculty of Engineering,
Hokkaido University, No. 79 (1976)

Uniaxial Plannar-Stress and Stress-Induced Anisotropy in Magnetic Films

Masayoshi SATŌ*

(Received September 27, 1975)

Abstract

Assuming that a polycrystalline magnetic film is composed of randomly-oriented small crystallites and that a uniaxial planar-stress is present in each crystallite, magnetic anisotropies resulting from this uniaxial stress are calculated for the crystallites with (001), (110) and (111) surfaces. Large uniaxial anisotropies result from the uniaxial planar-stress in each crystallite with (001), (110) and (111) surfaces, compared with the isotropic planar-stress which induces uniaxial anisotropy only in crystallites with a (110) surface. Anomalously large magnetocrystalline anisotropy observed in the (100) surface of single-crystal nickel films and large uniaxial anisotropy observed in the (110) surface of single-crystal permalloy films, which have been expained by the contribution of the isotropic planar-stress, are also explained by the contribution of the uniaxial planar-stress.

1. Introduction

It is well known that there is angular dispersion of M-induced anisotropy in polycrystalline magnetic films[1,2]. Assuming that a polycrystalline film is an ensemble of randomly-oriented crystallites, angular dispersion is attributed to variations in the local anisotropy from crystallite to crycrystallite[1,3~5]. This local anisotropy is now considered to be magnetocrystalline anisotropy and/or the anisotropy resulting from magneto-elastic energy which is due to the internal stress in the films[4,5].

It has been reported that the magnetocrystalline anisotropy constant K_1 is anomalously large in the (100) surface of single-crystal nickel films epitaxially evaporated on the cleft (100) surface of rock salt[6~8], and that a large uniaxial anisotropy is present in the (110) surface of single-crystal permalloy films epitaxially evaporated on LiF (110) surface[9]. Both of anomalously large K_1 and large uniaxial anisotropy are now well explained by the contribution of an isotropic planar-stress in the films[6~9].

According to the results obtained by Cundall and King[3,4] for nickel and nickel-iron films, the local anisotropy can only be uniaxial anisotropy. A polycrystalline magnetic film is composed of randomly-oriented small crystallites. If the surfaces of these crystallites, which are parallel to the film plane, are assumed to be composed of (001), (110), and (111) planes, uniaxial anisotropy results from the isotropic planar-stress only in the crystallites with a (110) surface. In an attempt to obtain the uniaxial local-anisotropy in each crystallite, it is assumed in this work that a uniaxial planar-stress is present in each crystallite. The possibility of the presence of this uniaxial stress has also been proposed by Smith

* Department of Electronic Engineering, Hokkaido University, Sapporo, 060, Japan.

et al.[10] and the anisotropy energy resulting from the randomly-oriented internal stress has been discussed briefly by Lewis[11] in the (011) plane of bulk nickel-iron alloys. The results obtained from the uniaxial planar-stress are that large uniaxial anisotropy is presesent in each crystallite with (001), (110), and (111) surfaces, and that both of anomalously large K_1 in the (100) surface and large uniaxial anisotropy in the (110) surface can be explained by this uniaxial planar-stress.

2. Anisotropy Resulting from Uniaxial Planar-Stress

It is assumed that a polycrystalline magnetic film of volume V is composed of randomly-oriented N small-crystallites of volume v_j:

$$V=\sum_{j=1}^{N} v_j \tag{2.1}$$

and that each crystallite is a single crystal. If a uniaxial planar-stress σ which is tensile is present in a crystallite, magneto-elastic energy density of the crystallite is given by[12]

$$\begin{aligned}E_\sigma= &-h_1\sigma\{\alpha_1^2\gamma_1^2+\alpha_2^2\gamma_2^2+\alpha_3^2\gamma_3^2-(1/3)\}-h_2\sigma(2\alpha_1\alpha_2\gamma_1\gamma_2+2\alpha_2\alpha_3\gamma_2\gamma_3+2\alpha_3\alpha_1\gamma_3\gamma_1)\\ &-h_4\sigma\{\alpha_1^4\gamma_1^2+\alpha_2^4\gamma_2^2+\alpha_3^4\gamma_3^2+(2/3)s-(1/3)\}-h_5\sigma(2\alpha_1\alpha_2\alpha_3^2\gamma_1\gamma_2+2\alpha_2\alpha_3\alpha_1^2\gamma_2\gamma_3+2\alpha_3\alpha_1\alpha_2^2\gamma_3\gamma_1)\\ &-h_3\sigma\{s-(1/3)\} \qquad \text{for} \quad K_1<0,\end{aligned} \tag{2.2}$$

where h_i are the single-crystal magnetostriction constants, α_i and γ_i are the direction cosines of the magnetization and the uniaxial stress relative to the cubic axis, respectively, and $s=\alpha_1^2\alpha_2^2+\alpha_2^2\alpha_3^2+\alpha_3^2\alpha_1^2$. To simplify the problem, the surfaces of the crystallites, which are parallel to the film plane, are assumed to be composed of the principal crystallographic planes, of the {001}, {110}, and {111} families.

For the crystallites with a (001) surface, magneto-elastic energy density is obtained from Eq. (2.2) as

$$\begin{aligned}E_\sigma^{(001)}= &-\{2(h_1+h_4)\sin^2\delta-h_1-(4/3)h_4\}\sigma\sin^2\theta-(1/3)h_4\sigma\sin^4\theta\\ &-(1/2)h_2\sigma\sin 2\delta\sin 2\theta-(1/4)h_3\sigma\sin^2 2\theta,\end{aligned} \tag{2.3}$$

where θ is an angle between $\langle 100\rangle$ direction and the direction of the magnetization and δ is an angle detween $\langle 100\rangle$ and the direction of the uniaxial stress. Magnetic torque $L^{(001)}$ which results from $E_\sigma^{(001)}$ is given by $-\partial E_\sigma^{(001)}/\partial\theta$, and

$$L^{(001)}=K_u^{(001)}\sin 2(\theta+\varphi^{(001)})+K_b^{(001)}\sin 4\theta, \tag{2.4}$$

where

$$K_u^{(001)}=[\{(h_1+h_4)(2\sin^2\delta-1)\}^2+(h_2\sin 2\delta)^2]^{1/2}\sigma, \tag{2.5}$$

$$K_b^{(001)}=(1/6)(3h_3-h_4)\sigma \tag{2.6}$$

and

$$2\varphi^{(001)}=\tan^{-1}\frac{h_2\sin 2\delta}{(h_1+h_4)(2\sin^2\delta-1)}. \tag{2.7}$$

It is seen from Eq. (2.4) that $K_u^{(001)}$ is a uniaxial anisotropy constant and $K_b^{(001)}$ is a biaxial anisotropy constant. Because of the random orientation of the crystallite axis in the film plane, δ varies from crystallite to crystallite in the range of 0 to 180 degrees. Accordingly, the values of $K_u^{(001)}$ and $\varphi^{(001)}$ vary from crystallite to crystallite as seen from Eqs. (2.5) and (2.7), respectively.

For the crystallites with a (110) surface, magneto-elastic energy density is obtained from Eq. (2.2) as

$$E_\sigma^{(110)}=-\{(1/2)(3h_1+h_2)\sin^2\delta-h_1\}\sigma\sin^2\theta-(1/2)h_2\sigma\sin 2\delta\sin 2\theta, \tag{2.8}$$

where θ is an angle between $\langle 001\rangle$ and the direction of magnetization and δ is an angle between ⟨001⟩ and the direction of the uniaxial stress. Magnetic torque $L^{(110)}$ is given by

$$L^{(110)}=K_u^{(110)}\sin 2(\theta+\varphi^{(110)}), \tag{2.9}$$

where

$$K_u^{(110)}=[\{(1/2)(3h_1+h_2)\sin^2\delta-h_1\}^2+(h_2\sin 2\delta)^2]^{1/2}\sigma \tag{2.10}$$

and

$$2\varphi^{(110)}=\tan^{-1}\frac{h_2\sin 2\delta}{(1/2)(3h_1+h_2)\sin^2\delta-h_1}. \tag{2.11}$$

It is seen from Eq. (2.9) that $K_u^{(110)}$ is a uniaxial anisotropy constant. It is also seen from Eqs. (2.10) and (2.11) that the values of $K_u^{(110)}$ and $\varphi^{(110)}$ vary from crystallite to crystallite.

For the crystallites with a (111) surface, magneto-elastic energy density is obtained from Eq. (2.2) as

$$\begin{aligned}E_\sigma^{(111)}=&-(1/3)(h_1+2h_2-h_5)(2\sin^2\delta-1)\sigma\sin^2\theta\\&-(2/9)(h_4+2h_5)(2\sin^2\delta-1)\sigma\sin^4\theta\\&-(1/6)\{h_1+2h_2+(1/3)h_5\}\sigma\sin 2\delta\sin 2\theta\\&-(1/18)h_5\sigma\sin 2\delta\sin 4\theta,\end{aligned} \tag{2.12}$$

where θ is an angle between $\langle 1\bar{1}0\rangle$ and the direction of the magnetization and δ is an angle between $\langle 1\bar{1}0\rangle$ and the direction of the uniaxial stress. Magnetic torque $L^{(111)}$ is given by

$$L^{(111)}=K_u^{(111)}\sin 2(\theta+\varphi_1^{(111)})+K_b^{(111)}\sin 4(\theta+\varphi_2^{(111)}), \tag{2.13}$$

where

$$K_u^{(111)}=[\{(1/9)(3h_1+6h_2+2h_4+h_5)(2\sin^2\delta-1)\}^2+\{(1/9)(3h_1+6h_2+h_5)\sin 2\delta\}^2]^{1/2}\sigma, \tag{2.14}$$

$$K_b^{(111)}=[\{-(1/9)(h_4+2h_5)(2\sin^2\delta-1)\}^2+\{(2/9)h_5\sin 2\delta\}^2]^{1/2}\sigma, \tag{2.15}$$

$$2\varphi_1^{(111)}=\tan^{-1}\frac{(3h_1+6h_2+h_5)\sin 2\delta}{(3h_1+6h_2+2h_4+h_5)(2\sin^2\delta-1)} \tag{2.16}$$

and

$$4\varphi_2^{(111)}=\tan^{-1}\frac{-2h_5\sin 2\delta}{(h_4+2h_5)(2\sin^2\delta-1)}. \tag{2.17}$$

It is seen from Eq. (2.13) that $K_u^{(111)}$ is a uniaxial anisotropy constant and $K_b^{(111)}$ is a biaxial anisotropy constant. It is also seen from Eqs. (2.14)～(2.17) that the values of $K_u^{(111)}$, $K_b^{(111)}$, $\varphi_1^{(111)}$, and $\varphi_2^{(111)}$ vary from crystallite to crystallite.

3. Numerical Results

For a nickel film, the values of $K_u^{(001)}$, $K_u^{(110)}$, and $K_u^{(111)}$ are calculated from Eqs. (2.5), (2.10), and (2.14), respectively, and the results are shown in Fig. 1 as functions of δ. Values of the single-crystal magnetostriction constants were taken from a paper by Bozorth and Hamming[13]. The values of $K_b^{(001)}$ and $K_b^{(111)}$ are also calculated from Eqs. (2.6) and (2.15), respectively. The value of $K_b^{(001)}$ is $-0.15\sigma\times 10^{-6}$ erg/cc, and the values of $K_b^{(111)}$ vary from crystallite to crystallite in the range of $(0.9\sim 1.7)\sigma\times 10^{-6}$ erg/cc. Accordingly, the values of biaxial anisotropy constants are much smaller than that of uniaxial anisotropy constants.

The directions of easy magnetization of the uniaxial anisotropies are calculated from Eqs. (2.4) and (2.7) for $K_u^{(001)}$, from Eqs. (2.9) and (2.11) for $K_u^{(110)}$, and from Eqs. (2.13) and (2.16) for $K_u^{(111)}$. The results are shown in Fig. 2 as functfons of

δ. In Fig. 2, the directions of easy magnetization are represented by the angles from ⟨100⟩ for $K_u^{(001)}$, from ⟨001⟩ for $K_u^{(110)}$, and from ⟨110⟩ for $K_u^{(111)}$.

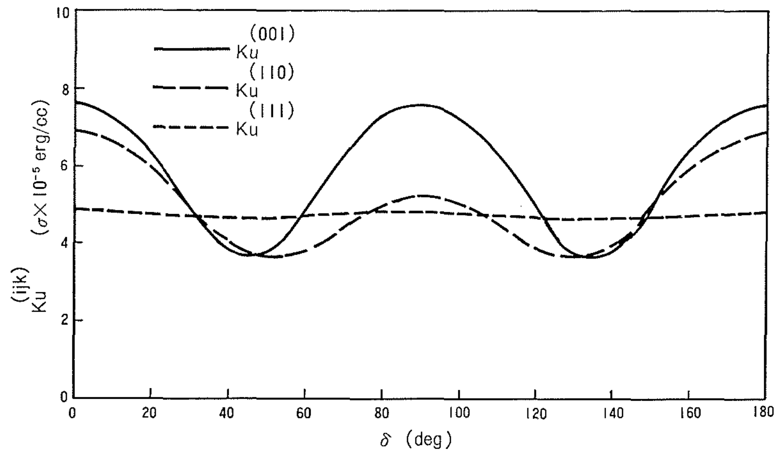

Fig. 1 Uniaxial anisotropy constants $K_u^{(001)}$, $K_u^{(110)}$ and $K_u^{(111)}$ of nickel film as functions of δ. δ are the angles between the direction of the uniaxial planar-stress σ and ⟨100⟩, ⟨001⟩ and ⟨1$\bar{1}$0⟩ for $K_u^{(001)}$, $K_u^{(110)}$ and $K_u^{(111)}$, respectively.

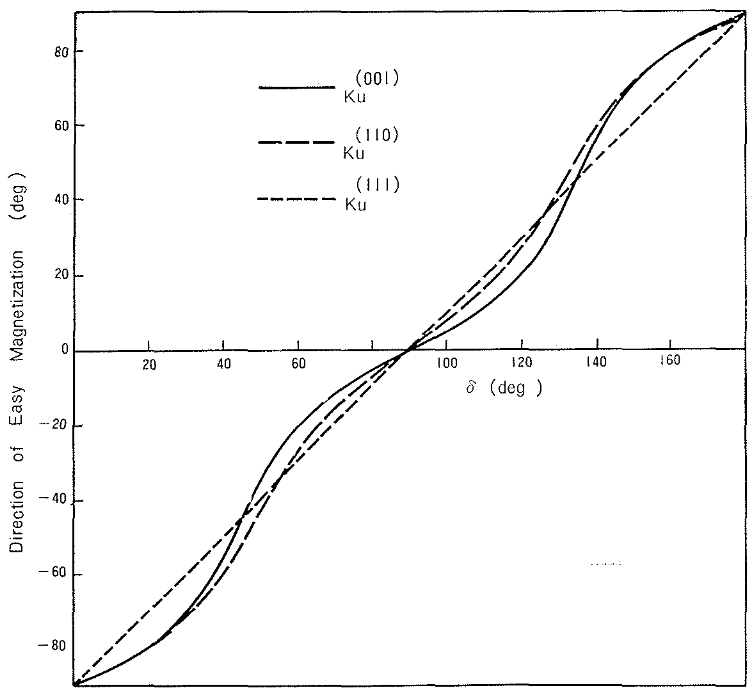

Fig. 2 Directions of easy magnetization of $K_u^{(001)}$, $K_u^{(110)}$ and $K_u^{(111)}$ of nickel film as functions of δ. Directions of easy magnetization are represented by the angles from ⟨100⟩, ⟨001⟩ and ⟨1$\bar{1}$0⟩ for $K_u^{(001)}$, $K_u^{(110)}$ and $K_u^{(111)}$, respectively.

4. Discussion

If a polycrystalline magnetic film is composed of randomly-oriented small crystsllites, the surfaces of these crystallites, which are parallel to the film plane, are composed of (001), (110), and (111) planes, and the isotropic planar-stress σ' is present in each crystallite, then, in each crystallite with a (001) surface, biaxial magnetic anisotropy results from σ', which is given by[7,8]

$$L'^{(001)}=K_b'^{(001)}\sin 4\theta, \tag{4.1}$$

where

$$K_b'^{(001)}=(1/3)(3h_3-h_4)\sigma' \tag{4.2}$$

and $K_b'^{(001)}=-0.3\sigma'\times 10^{-6}$ erg/cc for nickel film. In each crystallite with a (110) surface, uniaxial magnetic anisotropy results from σ', which is given by[9]

$$L'^{(110)}=K_u'^{(110)}\sin 2\theta, \tag{4.3}$$

where

$$K_u'^{(110)}=(1//2)(h_2-h_1)\sigma' \tag{4.4}$$

and $K_u'^{(110)}=16\sigma'\times 10^{-6}$ erg/cc for nickel film, which is much larger than the value of $K_b'^{(001)}$. In crystallites with a (111) surface, no magnetic anisotropy results from σ'. Accordingly, in the case of the isotropic planar-stess σ', uniaxial anisotropy is present only in the crystallites with a (110) surface and the value of the anisotropy consant $K_u'^{(110)}$ is the same in every crystallite.

On the other hand, if the uniaxial planar-stress σ is present in each crystallite, uniaxial anisotropies are present in every crystallite with (001), (110), and (111) surfaces, and the values of $K_u^{(001)}$, $K_u^{(110)}$, and $K_u^{(111)}$ vary from crystallite to crystallite in the range which is shown in Fig. 1. Moreover, the values of $K_u^{(001)}$, $K_u^{(110)}$, and $K_u^{(111)}$ are much larger than the value of $K_u'^{(110)}$. In both cases of σ and σ', the direction of the easy magnetization of the uniaxial anisotropy are distributed at random in the film plane because of the random orientation of the crystallite axis in the film plane.

As was stated in section. 1, an anomalously large K_1 in the (100) surface of a single-crystal nickel film and a large uniaxial anisotropy in the (110) surface of a single-crystal permalloy film are well explained by the contribution of the isotropic planar-stress σ': anomalously large K_1 is explained by the biaxial anisotropy given by Eqs. (4.1) and (4.2), and large uniaxial anisotropy is explained by the uniaxial anisotropy given by Eqs. (4.3) and (4.4).

A single-crystal film which is evaporated onto a substrate will be composed of many small-crystallites, but the orientation of the crystallite axis is not random. If a uniaxial planar-stress σ is present in each crystallite, and the dirction of σ is distributed at random in the film plane, magneto-elastic energy densities of the crystallites in single-crystal films with (100), (110), and (111) surfaces are given by Eqs. (2.3), (2.8), and (2.12), respectively. In order to obtain magneto-elastic energy density of a single-crystal film, the average of that of the crystallites must be taken in all of the possible directions of σ in each film. From the average of Eq. (2.3) with respect to δ from 0 to 180 degrees, we obtain the magnetic torque $\overline{L}^{(100)}$, and biaxial anisotropy constant $\overline{K}_b^{(100)}$ for the (100) surface of a single-crystal film, which is given by

$$\overline{L}^{(100)}=\overline{K}_b^{(100)}\sin 4\theta, \tag{4.5}$$

where

$$\overline{K}_b^{(100)}=(1/6)(3h_3-h_4)\sigma. \tag{4.6}$$

From the average of Eq. (2.8), we obtain the magnetic torque $\overline{L}^{(110)}$, and uniaxial anisotropy constant $\bar{K}_u^{(110)}$ for the (110) surface of a single-crystal film, which is given by

$$\bar{L}^{(110)} = \bar{K}_u^{(110)} \sin 2\theta, \tag{4,7}$$

where

$$\bar{K}_u^{(110)} = (1/4)(h_2 - h_1)\sigma. \tag{4.8}$$

From the average of Eq. (2.12), we can not obtain magnetic anisotropy; there is no megnetic anisotropy due to σ in the (111) surface of a single-crystal film.

From the uniaxial planar-stresses σ in crystallites, whose directions are distributed at random, we obtain the isotropic planar-stress σ' in the film by the relation $\sigma' = (1/2)\sigma$. Accordingly, $\bar{K}_b^{(100)}$ given by Eq. (4.6) and $\bar{K}_u^{(110)}$ given by Eq. (4.8) become the same as $K_b'^{(001)}$ given by Eq. (4.2) and $K_u'^{(110)}$ given by Eq. (4.4), respectively. These results mean that both the anomalously large K_1 in the (100) surface and large uniaxial anisotropy in the (110) surface can be explained by the uniaxial planar-stresses σ which are present in the crystallites.

Cundall and king[4] have deduced the magnitudes of the local uniaxial anisotropies in polycrystalline nickel and nickel-iron films from rotational hysteresis measurements, and the largest value of the local anisotropy constant was about 1×10^5 erg/cc in polycrystalline nickel film. If we take the value of the isotropic stress $\sigma'(2 \times 10^9$ dyne/cm) which is used by Lewis[14], we obtain from Eq. (4.4) the value of the anisotropy constant 0.32×10^5 erg/cc which is much smaller than 1×10^5 erg/cc. If we take the value of the uniaxial stress σ which is given by $2\sigma'$, we obtain from Fig. 1 the largest value of the anisotropy constant 3×10^5 erg/cc which is large enough to explain the experimental results.

Acknowledgment

The author wishes to thank prof. J. Muguruma and Dr. K. shima for their valuable discussions regarding the uniaxial planar-stresses in the crystallites.

References

1) Smith, D. O.: J. Appl. Phys. 32 (1961) 70 S.
2) Doyle, W. D.: J. Appl. Phys. 33 (1962) 1769.
3) Cundall, J. A. and King. A. P.: Phys. Stat. Sol. 16 (1966) 613.
4) Cundall, J. A. and King, A. P.: Proc. Internat. Conf. Magnetism (1964) 847.
5) Hornreich, R. M., Rubinstein, H. R. and Spain, R. J.: IEEE Trans. Magn. MAG-7 (1971) 29.
6) Chikazumi, S.: J. Appl. Phys. 32 (1961) 81 S.
7) Freedman, J. F.: J. Appl. phys. 33 (1962) 1148.
8) Secemski, E. and Anderson, J. C.: J. Phys. D 4 (1971) 574.
9) Tokutake, H. and Maejima, R.: J. Phys. Soc. Japan 20 (1965) 632.
10) Smith, D. O., Cohen, M. S. and Weiss, G. P.: J. Appl. phys. 31 (1960) 1755.
11) Lewis, B.: Brit. J. Appl. Phys. 15 (1964) 407.
12) Chikazumi, S.: Physics of Magnetism, J. Wiley and Sons (1964) 172.
13) Bozorth, R. M. and Hamming, R. W.: Phys. Rev. 89 (1953) 865.
14) Lewis, B.: Brit. J. Appl. phys. 15 (1964) 531.